



## Practical limitations for the bi-polar pulse sputtering of Al<sub>2</sub>O<sub>3</sub> with rotary magnetron targets using a reactive voltage controller

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### ABSTRACT

The high refractive index, superior electrical insulating properties, and physical encapsulation properties make aluminum oxide essential in many thin film stacks. The relatively slow sputter rate coupled with the high cost and complexity of advanced reactive process controllers often restricts the number of applications in which aluminum oxide is used. In this paper, the limitations for aluminum oxide reactive sputter deposition rate and film properties are explored for dual rotary magnetrons operating off a bi-polar pulse DC power supply. Sputtering hardware and process control optimization are implemented to maximize the deposition rates without reducing film quality. The impacts of several key variables are explored to provide process engineers with a thorough understanding of the hardware and process control requirements for an optimized reactive sputtering process.

### INTRODUCTION

The use of sputtered aluminum oxide in thin film stacks has gained popularity in the past few years due to the high refractive index, electrical insulating properties, and physical encapsulation properties. Aluminum oxide is used in application such as the passivation of silicon solar cells, the encapsulation of OLED devices, and various optical film stacks. The main drawbacks to depositing aluminum oxide for many applications are the low sputter rate and high probability of arcing when the target is in full oxide "Poison Mode". To overcome these limitations, aluminum oxide is sputtered in a reactive oxide process regime using argon and oxygen to sputter and react with the aluminum on the surface of the target instead of oxidizing the surface prior to sputtering.

The higher sputter rate of aluminum metal allows for higher deposition rates; however the formation

of the insulating aluminum oxide still limits the process due to the achievable plasma power density, process stability, and the relatively small process window in which the film is still a full oxide. Insulating oxide films form on all surfaces outside the sputter zone of the target and typical sputtering pressures in the range of 1 to 10mTorr allow for these films to form on surfaces outside the direct line of sight of the target due to gas scattering. The same gas scattering effect allows stray ions to come in contact with these insulating layers leading to charging of the insulating surface which can generate destructive arcs which can contaminate the substrate with larger particles and interfere with the process stability. Planar magnetrons suffer from arcing oxide problems due to the edge interface between the sputtered and unsputtered regions on the target surface that completely surround the plasma. On rotary magnetron targets the edge interface between the sputtered and unsputtered range is limited only to the ends of the target reducing the chance of arcing and contaminating the substrate.

The use of a Bi-Polar DC power supply for sputtering aluminum oxide in the reactive process region reduces process stability concerns that are found in straight DC processes. Bi-Polar Pulse DC requires 2 cathodes on a single circuit and while one cathode is sputtering the other cathode is the anode. The alternating between cathode and anode for the two targets eliminates problems associated with the disappearing anode effect that is a large concern when depositing insulating films.

### EXPERIMENTAL SETUP

A box shaped vacuum system with a vertical drum in the center was used for this testing. The ultimate base pressure of this system is 5x10<sup>-6</sup> Torr and it is pumped with two ISO-250 turbo molecular pumps. There are two SC Series Side Mount Cathodes

installed on the bottom of the chamber with 650mm long aluminum targets and QRM magnet bars. The power supply used to generate the plasma is an EN-Tech 30kW Bi-Polar Pulse Generator that operates at 40 kHz. A Gencoa Speedflo Mini with a power supply voltage input signal controlled a 100sccm Pneucleus Oxygen MFC and a Labview PID system with a 20mTorr capacitive manometer feedback controlled a 1000sccm Pneucleus Argon MFC. Both MFC's fed into a binary gas manifold that was positioned behind and between the two cathodes. The cathodes were also enclosed within a mini-chamber to provide an even pumping conductance between the gas manifold past both cathodes. A simplified top view of the system layout is shown in figure 1.

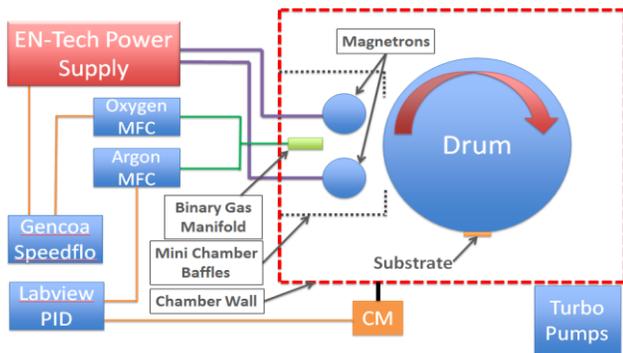


Figure 1: Simplified System Layout

### IDENTIFYING THE PROCESS SPACE

Each installation of rotary cathodes for a reactive oxide process will need to be calibrated due to variances in the gas delivery and pumping. The first step of that calibration process is to identify the process space. The shape of the process space hysteresis curve is shown in figure 2.

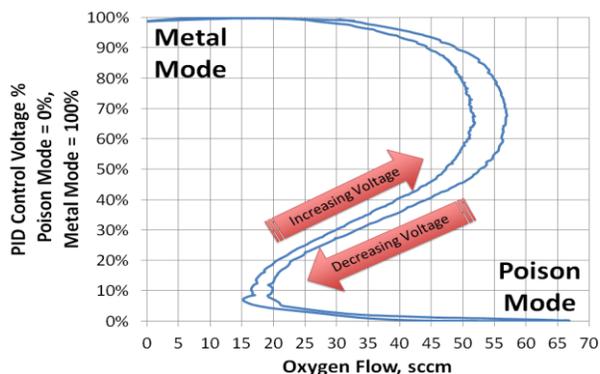


Figure 2: Example aluminum oxide process space curve

To map out the process space the magnetron was run in metal mode, pure argon only, to record the maximum voltage. When the metal mode voltage stabilized the reactive process controller, in PID control mode, was used to introduce oxygen into the chamber and increased until the addition of more oxygen no longer made significant changes in the voltage, Poison Mode. The process was repeated in reverse to measure the voltage as it increases from poison mode to metal mode. Gencoa's Speedflo software has a function that can record the voltage and oxygen flow data from metal mode to poison mode and back allowing for the creation of plots just like the one in figure 2.

The oxygen partial pressure is not the only factor that has an impact on the reactive sputtering process space. Background pressure and vacuum system conductance can also play a large role in defining the process space. The lower limit of the process space, poison mode, has little to no variation in the process voltage as a function of pressure, as seen in figure 3.

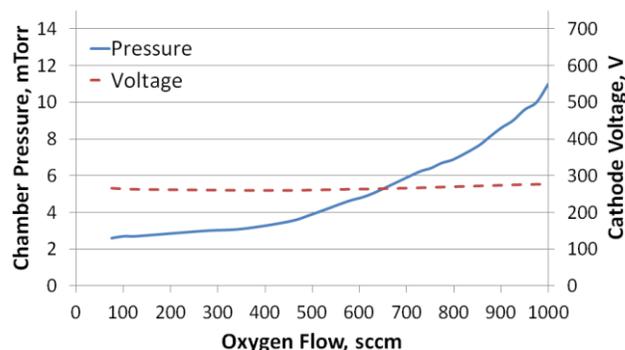
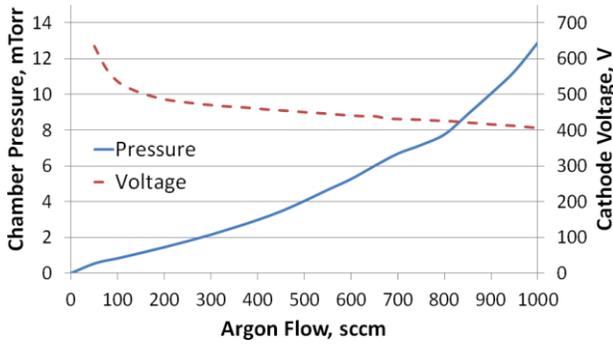


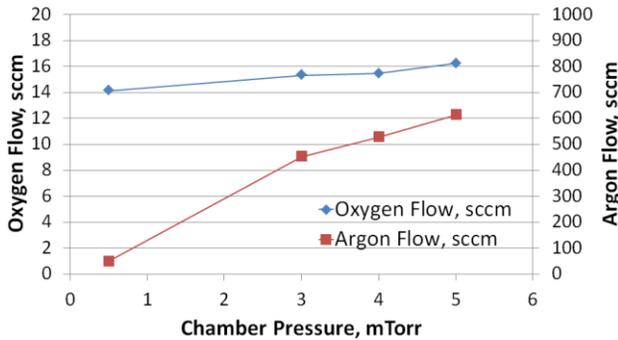
Figure 3: Cathode voltage and chamber pressure as a function of oxygen flow for 650mm long aluminum targets run at 10kW

The upper limit of the process space, full metal mode, is highly dependent on operating pressure as shown in figure 4.



**Figure 4: Cathode voltage and chamber pressure as a function of argon flow for 650mm long aluminum targets run at 10kW**

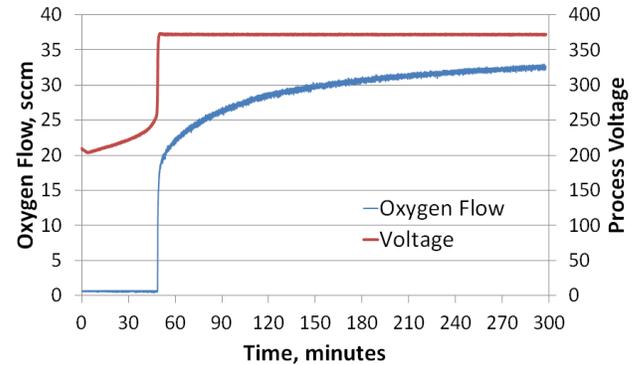
The large variation from 400V to 650V as an upper limit indicates that the system pressure as a function of the argon flow is very important to monitor. A neighboring process could easily shift the upper limit down after initial calibration causing the final process to run closer to metal mode, this can produce different film properties that may not function properly in the film stack. This variation requires that the system needs to be calibrated for each pressure that the cathode is run at to maintain a consistent process set point. Figure 5 shows how the argon and oxygen flow rates change in relationship to each other for the same reactive process set point at different pressures.



**Figure 5: Oxygen and Argon flow as a function of chamber pressure for the RVC set to 15%**

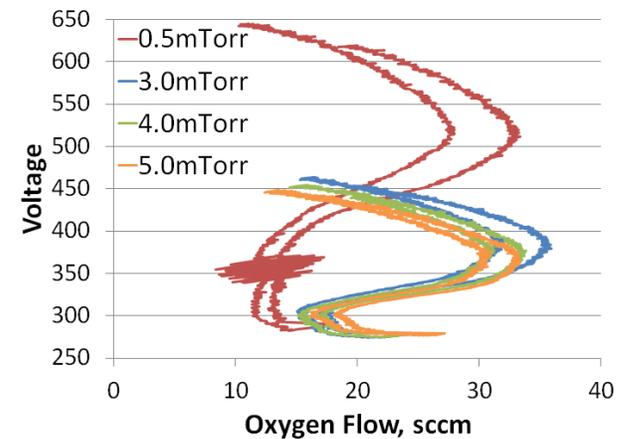
The background pressure due to water vapor also affects the process space by driving the process into the poison mode until the background pressure drops low enough to enable control over the process. To test the influence of the base pressure, the coater was vented, exposed to the atmosphere for 30 minutes, pumped down and as soon as it was crossed over to high vacuum, the cathodes were

started and the reactive voltage controller was set to 50% of metal mode. Figure 6 shows the results of this test. The process controller was not able to control the process for 47 minutes after crossover and the effects of the base pressure could still be seen after 5 hours of sputtering with the base pressure reaching  $3.2 \times 10^{-5}$  Torr.



**Figure 6: Oxygen flow and process voltage as a function of time after high vacuum crossover for RVC at 50%**

The process space factors can be seen more clearly when multiple process space hysteresis curves are plotted on the same graph as shown in figure 7. The open chamber plots in figure 7 have the lowest pressure thus the top end of process space extends all the way up to 650V while the higher pressure process spaces are limited to around 450V.



**Figure 7: Hysteresis curves plotted for various chamber pressures**

When the same plots are normalized by making setting the metal mode voltage to 100% and the poison mode voltage to 0% each process space shows roughly the same trends for the same

percentages. The normalized values are shown in figure 8.

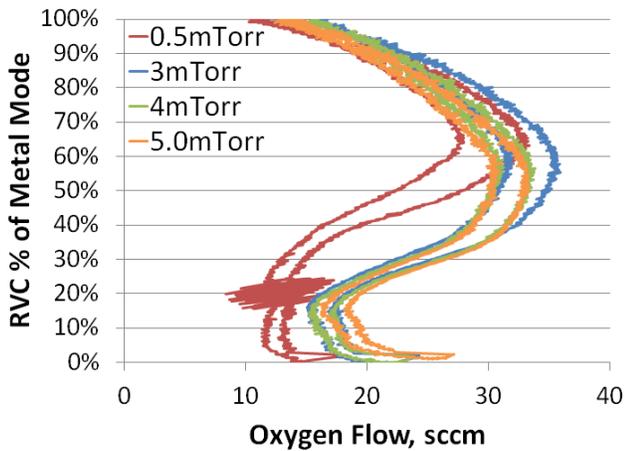


Figure 8: Normalized hysteresis curves

Once the process space has been identified, the process controller can be used to replicate the same deposition rate and coating properties as a function of the normalized percentage of the metal mode voltage. Figure 9 shows a hysteresis curve with measured deposition rates that correlate to position on the curve.

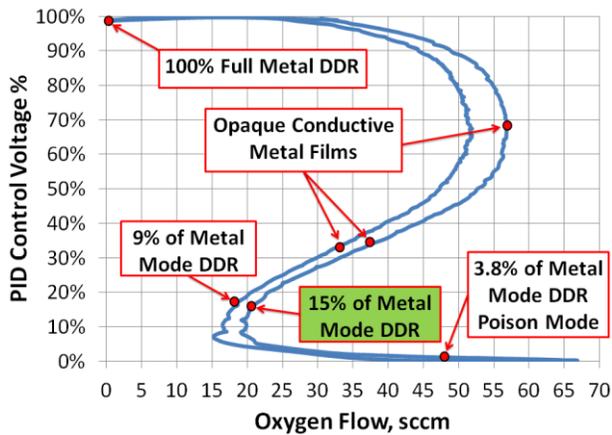


Figure 9: Deposition rates as a function position on the hysteresis curve

The maximum deposition rate reached was 15% of the metal mode dynamic deposition rate. The full oxide poison mode only produced a deposition rate of 3.8% of the metal mode rate so the maximum deposition rate that was reached at 15% of the metal mode voltage was roughly 4 times the poison mode deposition rate. The maximum stable power density at 15% of the metal mode voltage was

34kW/meter. Running a set of targets at this power rate produces a maximum dynamic deposition rate in the range of 40-50nm\*m/min.

### TARGET UTILIZATION

The utilization of the target material is a function of the sputtering geometry and the process set point on the hysteresis curve. The geometry of the plasma on the target surface is defined in figure 10.

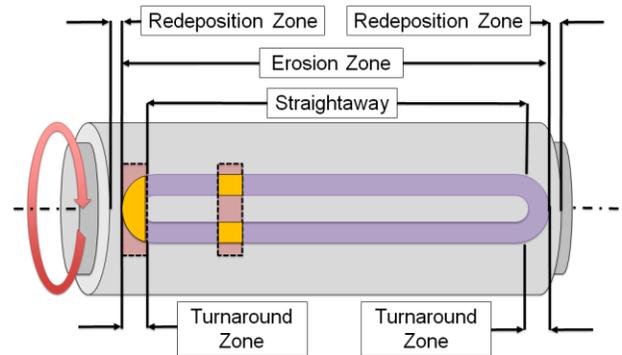


Figure 10: Target erosion zones with turnaround zone and straightaway zone surface area comparisons. The plasma is shown in purple and the yellow sections are to highlight the comparison between the surface areas of the straightaways and the turnarounds.

The turnaround zones have larger integrated surface areas in relation to the rotation direction of the target material when compared to the straightaways. The larger surface area of the turnarounds creates a condition where a higher sputter flux is produced which can shift the point on the hysteresis curve higher for the turnaround than the straightaways, increasing the sputter rate, reducing the target lifetime, reducing the target utilization, and possibly coating the substrate near the turnarounds with a material that would be more conductive and less transparent than the coating along the straightaway. To help reduce this inherent problem the QRM magnet bar has a stepped turnaround design as shown in figure 11.

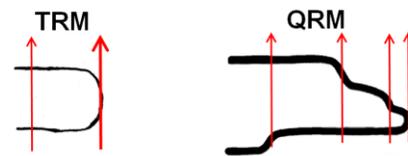
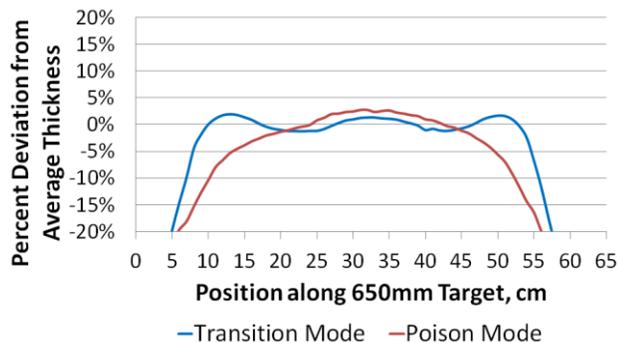


Figure 11: Turnaround design comparison

Breaking the turnaround up into multiple smaller turnarounds has the advantages of reducing the surface area differential between the turnaround and the straightaway, eliminating the need for a dogboned target profile, and increasing the deposition uniformity by reducing electron losses and the cross corner effect.

### DEPOSITION UNIFORMITY

The uniformity for full poison mode and the transition mode are shown in figure 12.



**Figure 12: Uniformity comparison between transition mode at 15% of the metal mode voltage and poison mode. Rates measured optically with a Filmetrics F-20.**

The humps on the transition mode curve indicate that the turnarounds are still running at a slightly higher point on the hysteresis curve which ends up producing higher deposition rates along with higher absorption rates. To reduce this effect a multi-zone gas manifold can be used to introduce slightly more oxygen to the turnaround bringing them back down to the same point on the hysteresis curve as the straightaways.

### CONCLUSIONS

The maximum deposition rate at 15% of the metal mode voltage is roughly 4 times the poison mode rate. The maximum power density at these settings is 34kW/meter of target length. The target utilization and film uniformity will depend heavily on differential of the hysteresis curve operating points between the turnarounds and the straightaway. The higher on the hysteresis curve the larger the potential differential can become possibly having negative effects on the uniformity and utilization. The negative effects can possibly be reduced by adding additional oxygen to the turnarounds which could also have the negative effect of reducing the maximum power stability. For maximum utilization, the closer the process can be run to poison mode the better the utilization will be but this will result in lower deposition rates.

### FUTURE WORK

To further characterize the limits of sputtering aluminum oxide with a bi-polar pulse power supply the target utilization at multiple points on the hysteresis curve need to be explored along with the effects of adding additional oxygen to the turnaround. The maximum power as a function of the additional oxygen added to the turnarounds also needs to be explored since there is a correlation between the increased production of insulating films at the turnaround and increased arcing.